State of the Art in EM Software for Microwave Engineers

White Paper

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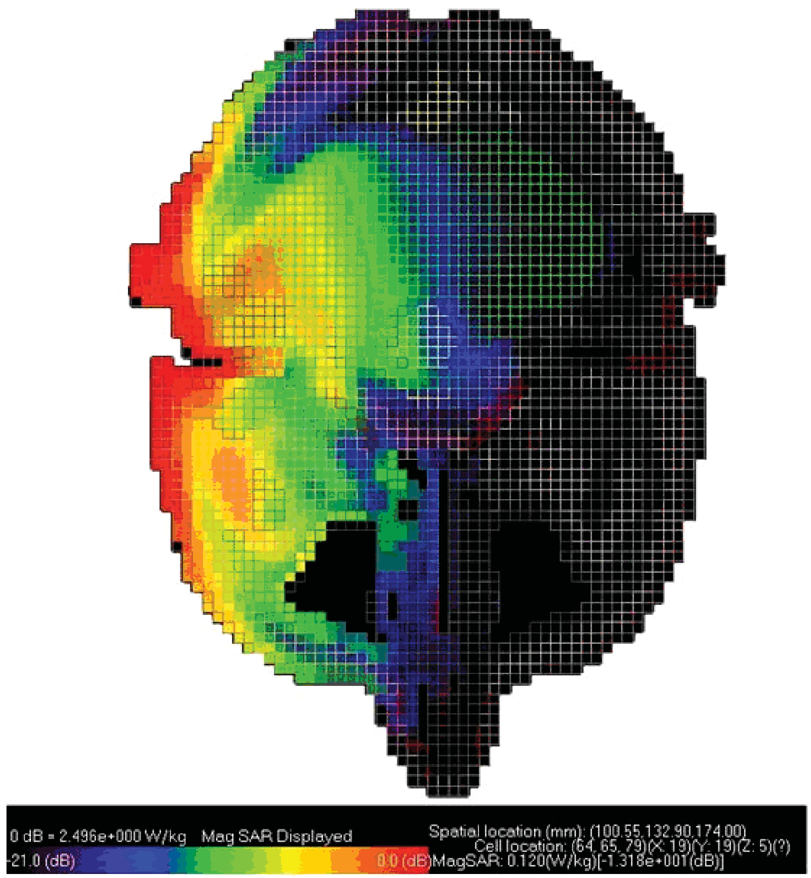
Introduction

The growing number and complexity of high frequency systems is leading to an increased need for electromagnetic (EM) simulation to accurately model larger portions of the system. There are several different technical approaches to EM simulation, and while no method is generally superior to the others, each one of them is aligned with one or more application areas. This article will discuss the three most established EM simulation technologies: Method-of-moments (MoM), finite element method (FEM) and finite difference time domain (FDTD), linking the simulation technology to solving specific applications.



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The method of moments

Overview of the method-of-moments

Among all techniques to solve EM problems, the method of moments (MoM) is one of the hardest to implement because it involves careful evaluation of Green's functions and EM coupling integrals. Maxwell's equations are transformed into integral equations which upon discretization yield the coupling matrix equation of the structure.

The advantage of this transform is that the current distributions on the metal surfaces emerge as the core unknowns. This is in contrast to other techniques which typically have the electric and/or magnetic fields (present everywhere in the solution space) as the core unknowns. Only the surfaces of the metals, where the currents flow, need to be taken into account in the meshing (Figure 1). Hence the number of unknowns (or the size of the matrix) is much smaller. This results in a very efficient simulation technique, able to handle very complex structures.

This benefit comes with a price as the integral equations are not applicable for general 3D structures. The key is the availability of the Green's functions. Computation of the Green's functions is only available for free space or for structures that fit in a layered stack up. These so-called 3D planar structures can have any shape in the plane of the layered stack, but can only have vertical geometry features (via's) in the normal direction. Many practical RF or microwave structures fall into this category. Hence the method of moments is a very wide-spread technique and commonly used for the simulation of printed antenna's, MMIC's, RF boards, SiPs, RFIC, SI structures and RF modules.

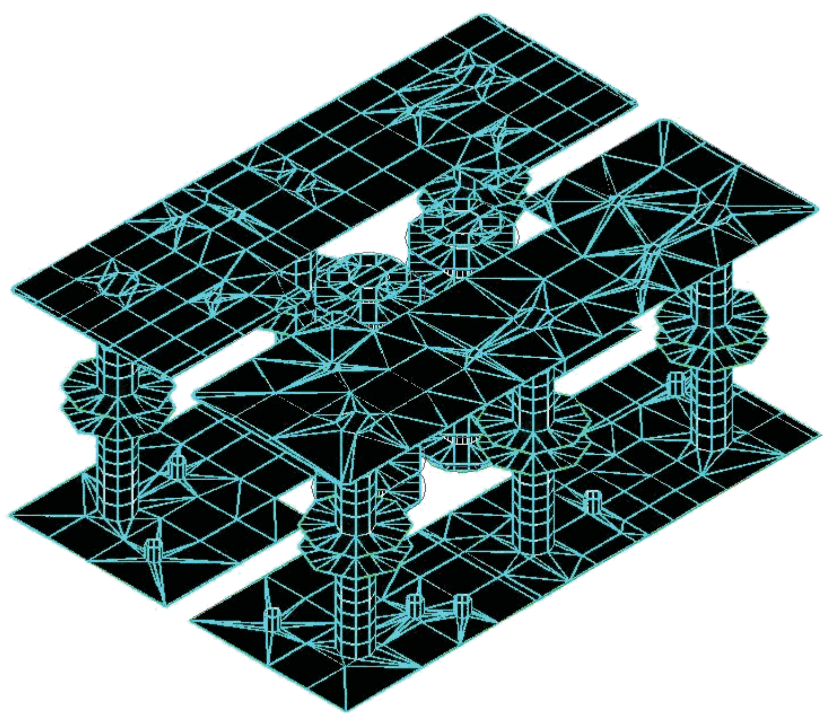

Figure 1. MoM discretization of a 3D planar structure (PCB differential via stubs)

Recent innovations in the method-of-moments

As data rates and signal frequencies keep on rising, the complexity of the electronic circuits that require EM simulation has gone up to such levels that existing MoM technology suffers from performance issues (both in capacity and speed). The main bottlenecks are in the storage and the solution of the huge dense coupling matrix. For a structure with N discrete elements, the memory storage requirement scales with N2 and the matrix solve time scales with N3 (when using a direct solver) or with N2 (when using an iterative solver). These scaling properties impose a roadblock on the performance to address very large and complex structures. A major break-through that recently emerged is the development of matrix compression techniques that reduce these scalings to NlogN. The benefits of NlogN technology in terms or memory usage and computation time are huge and grow with the complexity of the structures.

Application of the method-of-moments for printed circuit board simulations

With the enhancement of an NlogN matrix compression technique, a method of moments solver is very well prepared to handle very complex designs. As an example, we consider the simulation of differential via stubs in a 16 layer printed circuit board stack up (Figure 2). The example demonstrates the benefits of the MoM integral formulation. Note that the mesh used for the ground planes (Figure 1) contains only cells in the via anti-pad holes. The entire ground plane metallization is taken up in the kernels of the integral equations. The resulting matrix equation has only 5,539 unknowns.

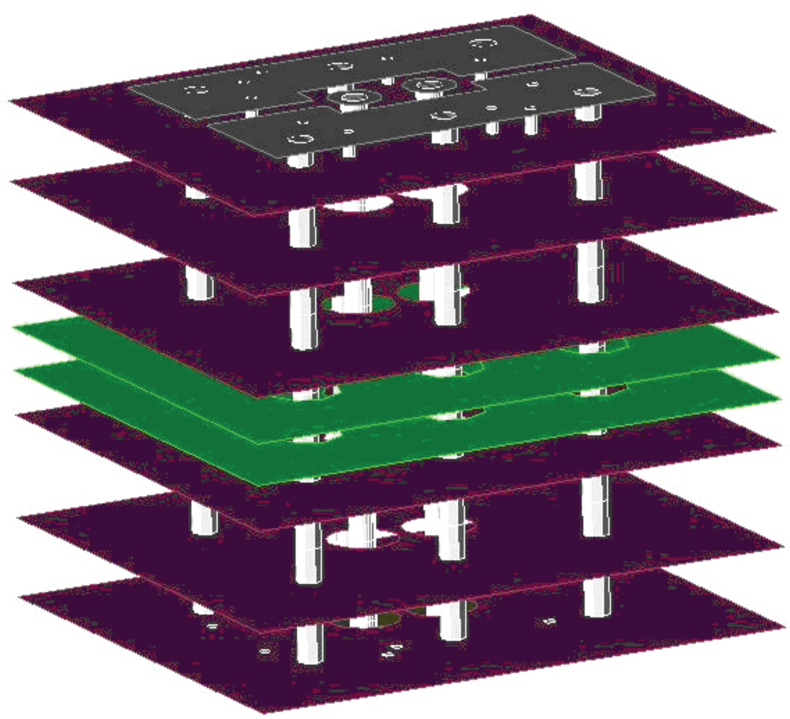

Figure 2. Differential via stubs in 16 layer PCB (geometry is stretched in vertical direction)

The broadband data for the simulated group delay and insertion loss are obtained in less then 10 minutes using the momentum simulator on a standard 4 core Linux machine. The correlation with measured data is shown in (Figure 3).

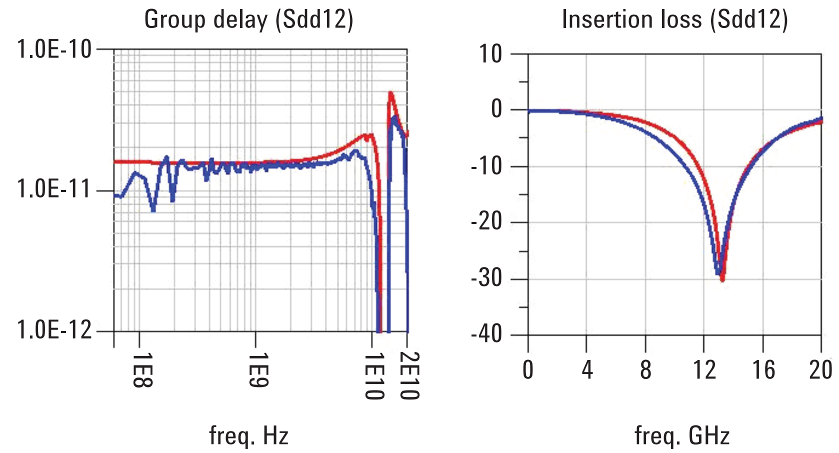

Figure 3. Simulated (red) and measured (blue) group delay and insertion loss

The authors wish to acknowledge Gustavo Blando (SUN Microwave Systems) for his aid in the preparation of this PCB example.

Finite element method

Overview of FEM method

FEM field solver has several advantages over MoM. For example, FEM solver can handle arbitrary shaped structures such as bondwires, conical shape vias, solder balls/bumps where z-dimensional changes appear in the structure. Moreover, FEM solvers can simulate dielectric bricks or finite size substrates. Many applications such as cavity designs require this capability. But it is generally slower than MoM especially for planar applications. (Figure 4) illustrates an example where FEM has advantages over regular MoM, particularly with respect to the general 3D nature of the structure.

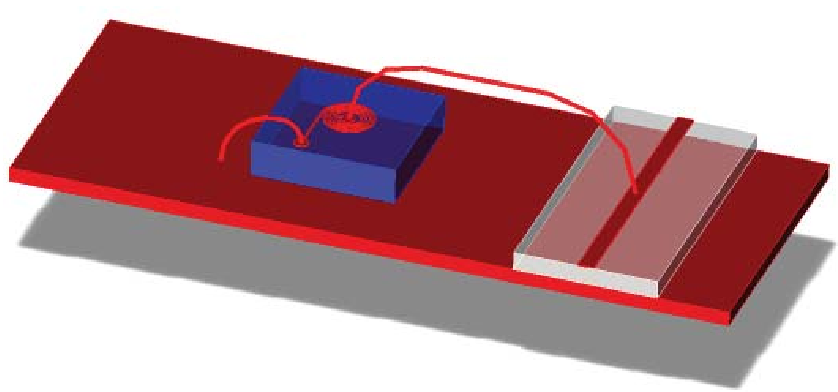

Figure 4. 3D FEM application example for spiral inductors with bond wires – bias network

FEM is based on volumetric meshing where the full problem space is divided into thousands of smaller regions and represents the field in each sub-region (element) with a local function. The geometric model is automatically divided into a large number of tetrahedra, where a single tetrahedron is formed by four equilateral triangles. This collection of tetrahedra is referred to as the finite element mesh.

The value of a vector field quantity (such as the H-field or the E-field) at points inside each tetrahedron is interpolated from the vertices of the tetrahedron. At each vertex, the components of the field that are tangential to the three edges of the tetrahedron are stored. In addition, the component of the vector field at the midpoint of selected edges that is tangential to a face and normal to the edge can also be stored. The field inside each tetrahedron is interpolated from these nodal values.

The components of a field that are tangential to the edges of an element are explicitly stored at the vertices. The component of a field that is tangential to the face of an element and normal to an edge is explicitly stored at the midpoint of the selected edges. The value of a vector field at an interior point is interpolated from the nodal values. By representing field quantities in this way, Maxwell's equations can be transformed into matrix equations that are solved using traditional numerical methods.

Integrated 3D EM into circuit design environment (ADS)

The FEM field solvers are used for various applications, however many design engineers use them in circuit design applications, such as transition designs, interconnect analysis, and so on. In a typical design flow, circuit design engineers draw structures and run EM simulations with a stand-alone FEM field solver and then bring the s-parameter data back to circuit design environment for the final design verification. However there are many unnecessary and redundant steps involved with this design flow, which are error prone, tedious, time consuming, and complicated.

By integrating FEM field solver into the circuit design environment, it is possible to reduce the total elapsed design time (time required from entering the design geometry to getting the final EM simulation results). Unnecessary layout data conversion, redundant import/export processes, custom tool development such as port generation utility are all eliminated with the integrated 3D EM design flow. EMDS for ADS is the FEM field solver that is fully integrated into ADS circuit design environment to serve this purpose.

Application example of FEM field solver for QFN package simulations

QFN (quad flat no-lead) is very popular low cost package solution for RFIC, MMIC, and RF SiP applications. It is very important for IC designers to understand the electrical performance of packages from the early stage of design process as the operating frequency of ICs goes up. What is the upper frequency limit that the package can operate and what is the isolation performance of the package? Is it possible to use a lower cost package to lower the final product cost?

16-pin, 3 x 3 [mm] QFN package performs fairly well up to 15 GHz, showing less than -18 dB return loss on a PCB. The QFN package with bond wires on the PCB can be easily drawn in a layout tool shown in (Figure 5) and quickly simulated with the integrated FEM field solver, EMDS for ADS. It is a lot easier for designers to draw in planar layout tools than 3D drawing tools.

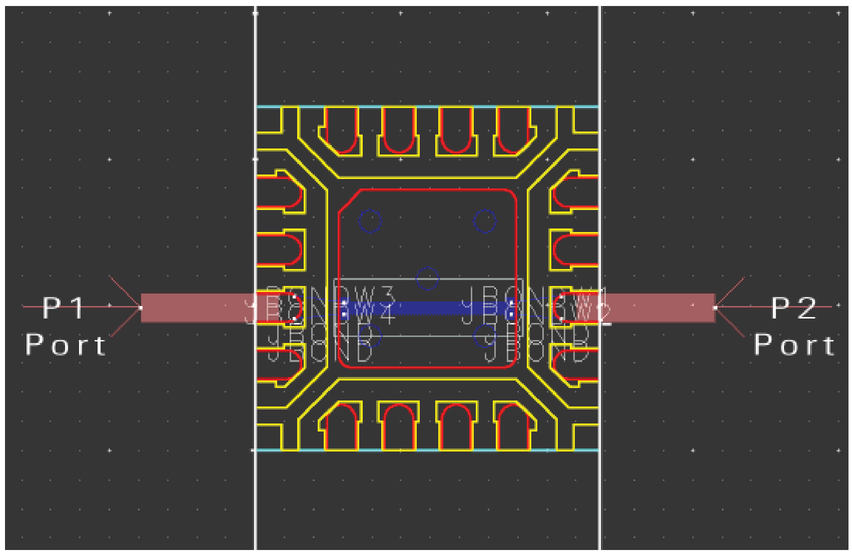

Figure 5. ADS layout of QFN package on PCB

The package performance can be improved by optimizing the transition design to maintain a good impedance profile throughout the transition, e.g. by using two leads instead of single lead and a wider transmission line, shown in (Figure 6).

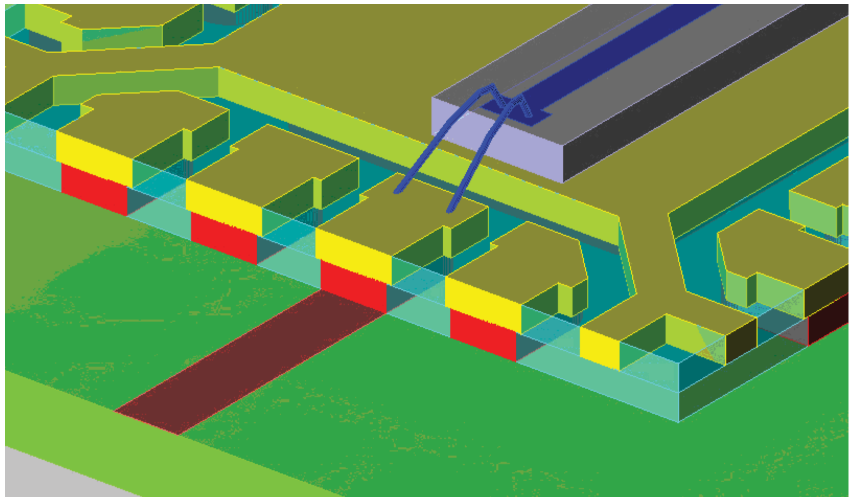

Figure 6a. Original design

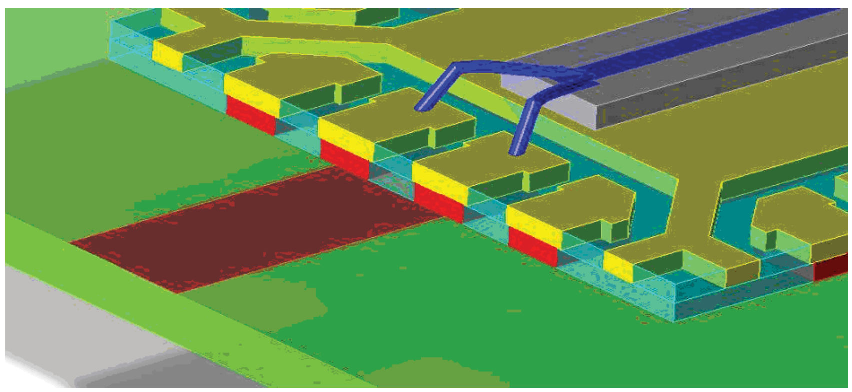

Figure 6b. Improved transition design

These changes can be easily made in the layout environment without import/export processes. (Figure 7) shows the improved performance of 3 x 3 QFN package with the aid of the integrated FEM field solver.

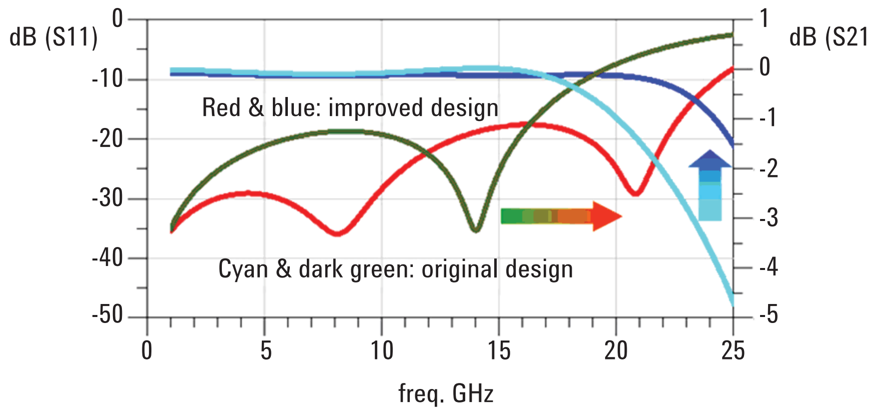

Figure 7. Improved QFN package performance

Finite difference time domain

Overview of FDTD

In contrast to the above described MoM and FEM algorithms, which only implicitly solve Maxwell's equations through the solution of a dense or sparse matrix, finite difference time domain (FDTD) algorithms [1]-[2] directly solve Maxwell's equations in a fully explicit way. Just as in the FEM, the unknowns in FDTD stem from a volumetric sampling of the electric and magnetic fields throughout the complete space (truncated in practice by absorbing boundary conditions). Whereas FEM-meshes typically consist of tetrahedrical cells, FDTD-meshes are typically built from rectangular cells, also called Yee cells. Being a marching-in-time procedure, the FDTD method updates the field values time-step by time-step (thereby explicitly following the electromagnetic waves as they propagate through the structure). As a result, a single FDTD simulation can provide data over an ultra-wide frequency range.

Because of its simple, robust nature and its ability to incorporate a broad range of (non)-linear materials and devices, FDTD is being used to study a wide range of applications: antenna design, microwave circuits, bio/EM effects, EMC/EMI problems, photonics.

Even more than for MoM- or FEM-based solvers, the popularity of FDTD-based solvers has been facilitated by recent advances in the speed and memory capacity of computer hardware. FDTD is an inherently parallel method and therefore lends itself very well to the processing capabilities of the most recent advances in CPU (general purpose processors) and GPU (graphics processors) hardware.

Application of FDTD to the study of the radiation by a mobile phone

Antenna systems for mobile phones are becoming more and more complex with every new generation. Antenna designers are not only challenged by technical requirements (multi-band, efficiency,...) but also by legal requirements (specific absorption ratio or SAR, hearing aid compatibility or HAC,...) and cost considerations. Further, many objects close to the antenna (battery, camera,...) have a strong influence on the antenna system's performance making it absolutely necessary to study the antenna inside the complete phone. The effect of real world interaction, such as the detuning of the antenna when the handset is close to the human body, has to be considered very early in the design cycle.

Due to its robust meshing, FDTD is currently the main algorithm for designing such complex mobile phone antenna systems. Figure 8 shows the detuning of the return loss of a mobile phone when held close to a head. The set-up was simulated with Agilent EEsof EDA's Electromagnetic Professional (EMPro). The mobile phone, head and hand were all imported from various types of CAD files. The design flow has been optimized for efficient re-iteration of such CAD-based complex designs allowing mobile appliance designers to simulate a large number of prototypes in rapid succession.

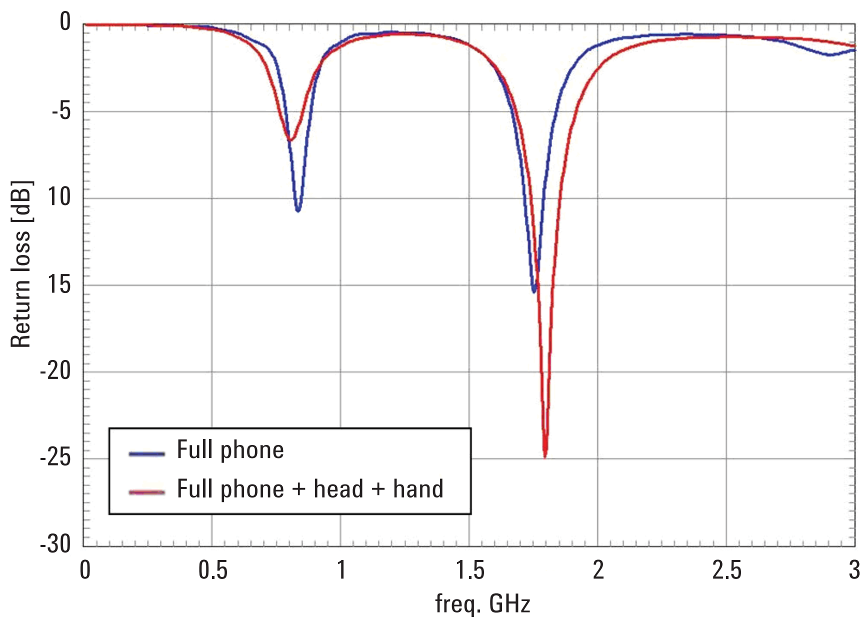

Figure 8. Distortion of the mobile-phone's return loss in the proximity of a head and hand

The advanced post-processing enables designers to determine very early in the design cycle whether or not a mobile phone is in accordance with the required legal standards. (Figure 9) shows the specific absorption ratio (SAR)-distribution inside the standard anthropomorphic model (SAM)-head caused by a mobile phone and the near-field values at a distance of 10 mm from the mobile phone's speaker output. The latter data enables designers to evaluate the hearing aid compatibility of the mobile phone.

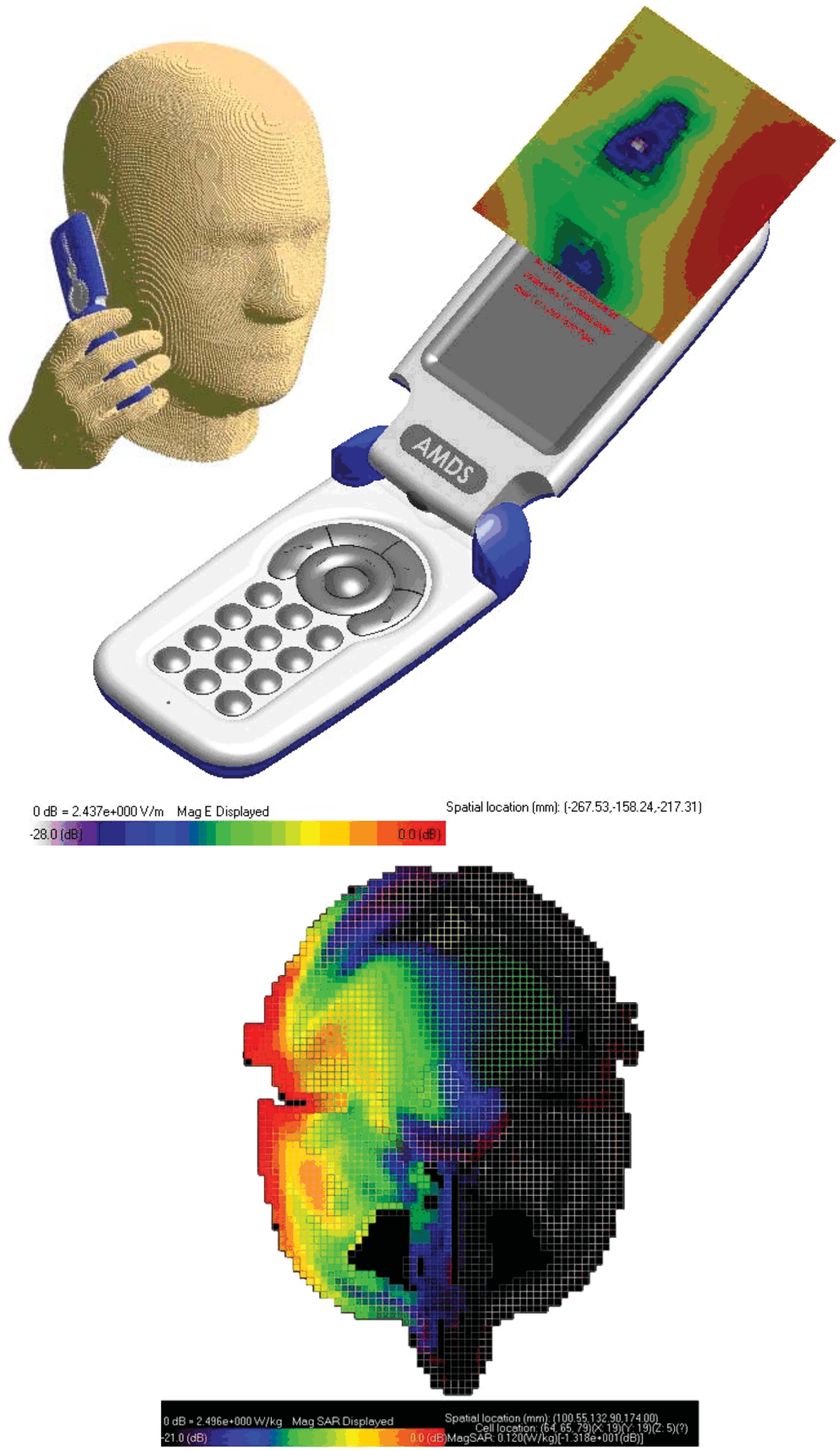

Figure 9. FDTD mesh-view of a mobile phone in proximity of a head and hand (top), SAR-distribution inside the SAM-head (middle) and near-field E-field distribution in the HAC scanning area (bottom)

Summary

This article showed the application of three main EM simulation technologies, demonstrating that MoM has specific advantages when simulating complex 3D planar structures, where FEM allows for additional 3D elements in the computation and where FDTD has advantages to solve geometrically complex 3D structures.

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[2] A. Taflove, S. Hagness, *Computational Electrodynamics*, 3rd ed., Artech House, 2005

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Revised: October 6, 2008

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